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(54) **DATA STORAGE DEVICE EMPLOYING MULTIPLE JOG PROFILES FOR A BUTTERFLY WRITTEN DISK SURFACE**

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(58) **Field of Classification Search**
None
See application file for complete search history.

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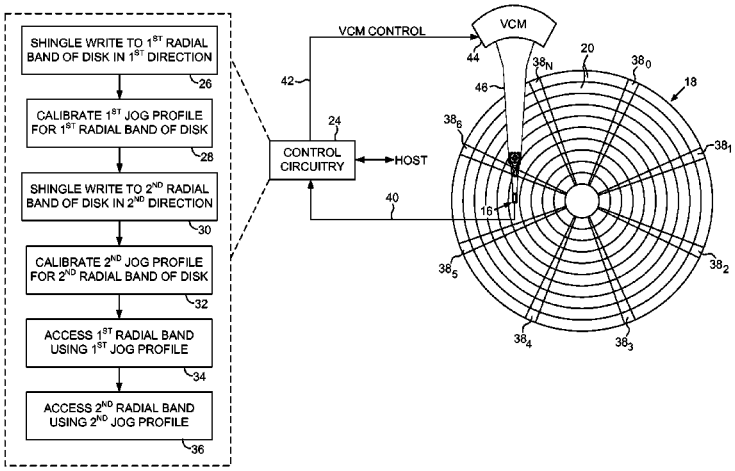
(57) **ABSTRACT**

A data storage device is disclosed comprising a head actuated over a disk comprising a plurality of data tracks, wherein the head comprises a write element radially offset from a read element by a writer/reader offset that varies relative to a radial location of the head over the disk. A first radial band (RB) of the data tracks is written from an outer diameter (OD) of the disk toward an inner diameter (ID) of the disk, and a first jog profile is calibrated for the first radial band that compensates for the writer/reader offset. A second RB is written from an ID to an OD, and a second jog profile is calibrated for the second RB that compensates for the writer/reader offset. The first RB is accessed using the first jog profile, and the second RB is accessed using the second jog profile.

12 Claims, 6 Drawing Sheets



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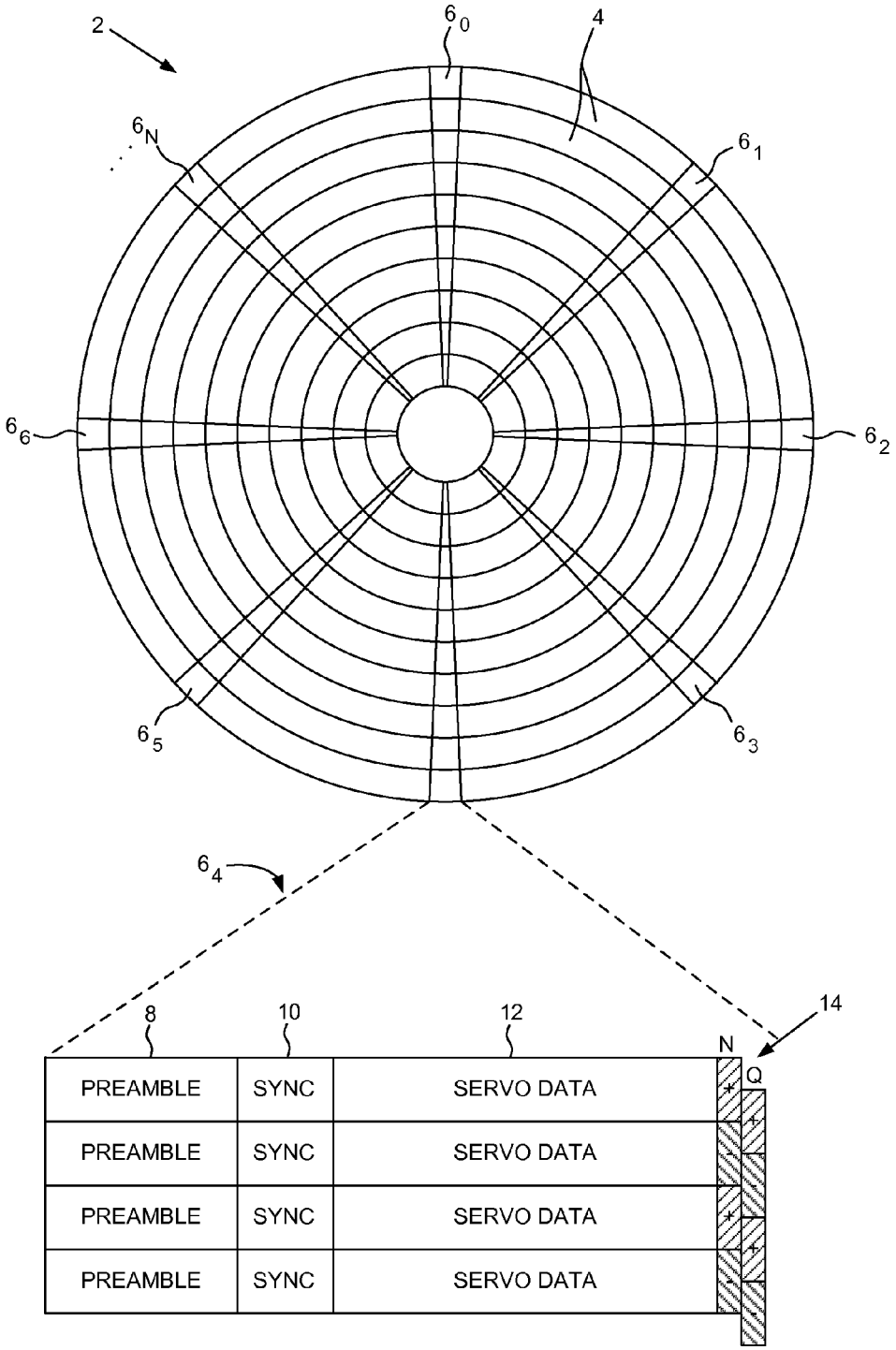

FIG. 1
(Prior Art)

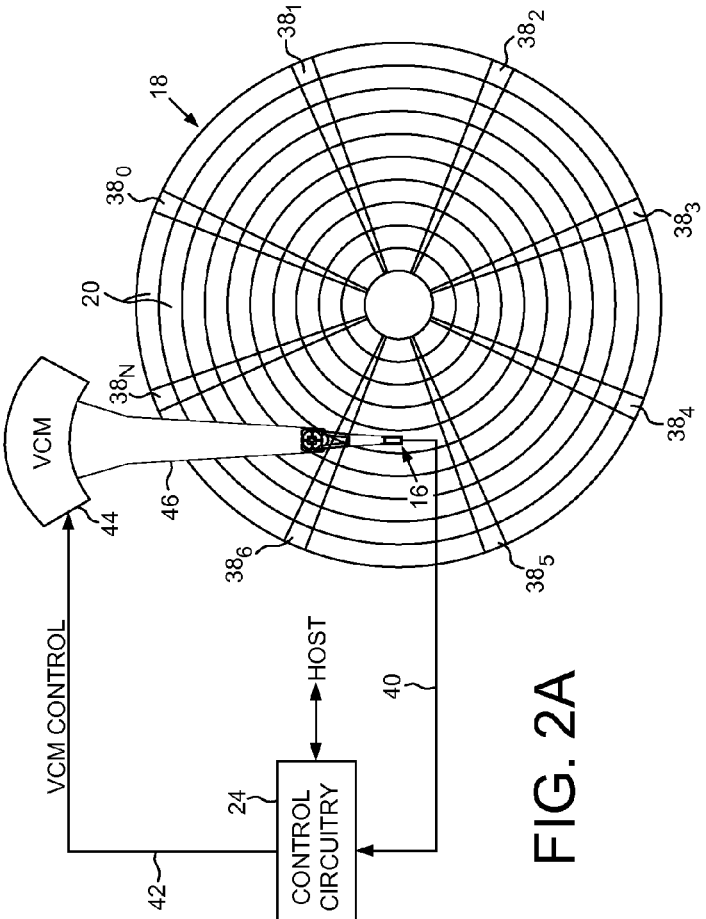

FIG. 2A

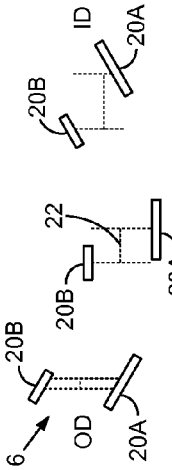

FIG. 2B

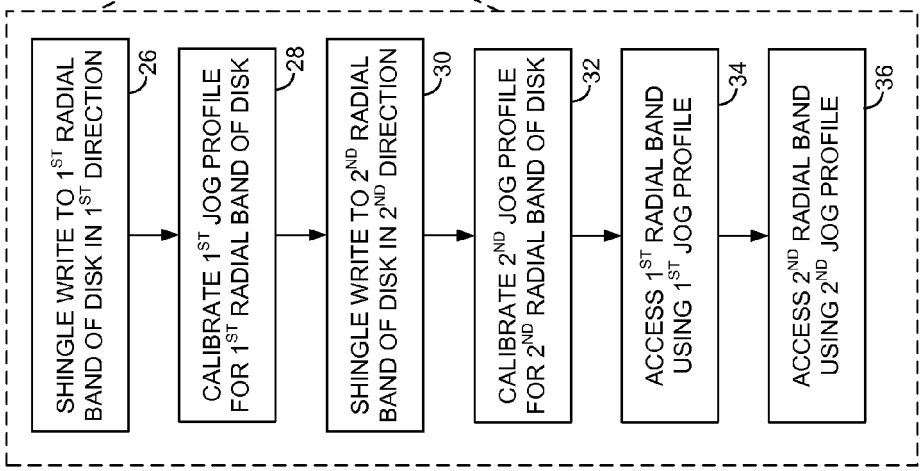

FIG. 2C

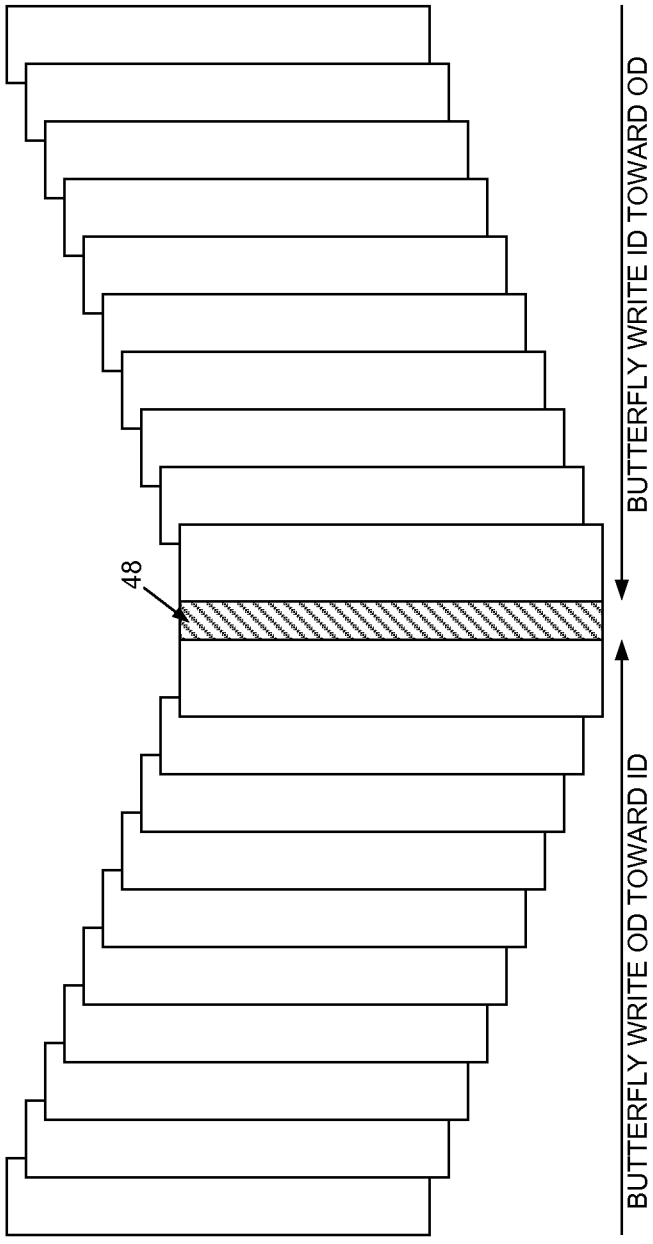
48
BUTTERFLY WRITE ID TOWARD OD
BUTTERFLY WRITE OD TOWARD ID

FIG. 3

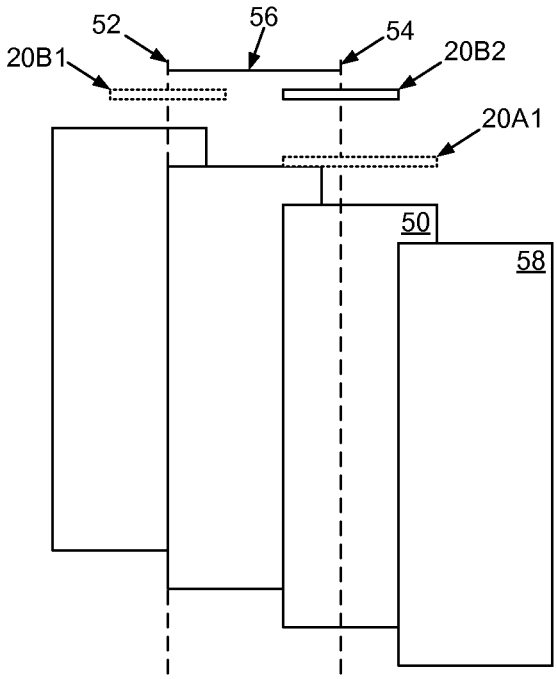

FIG. 4A

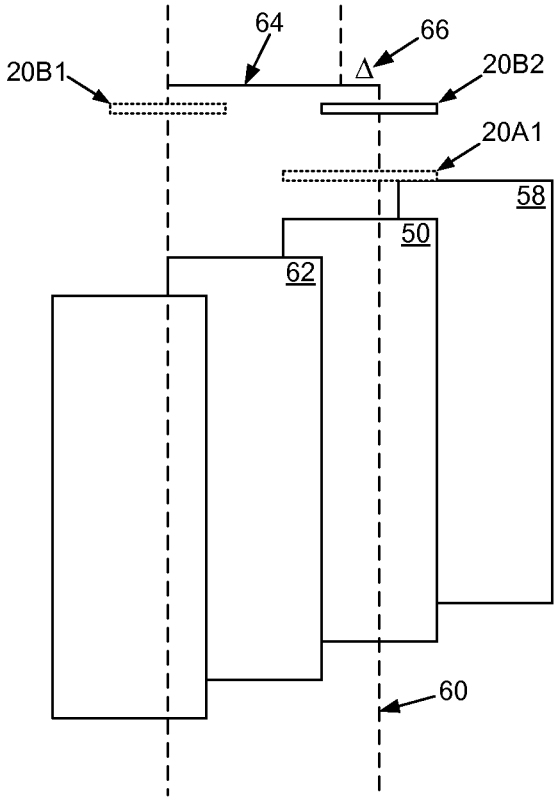

FIG. 4B

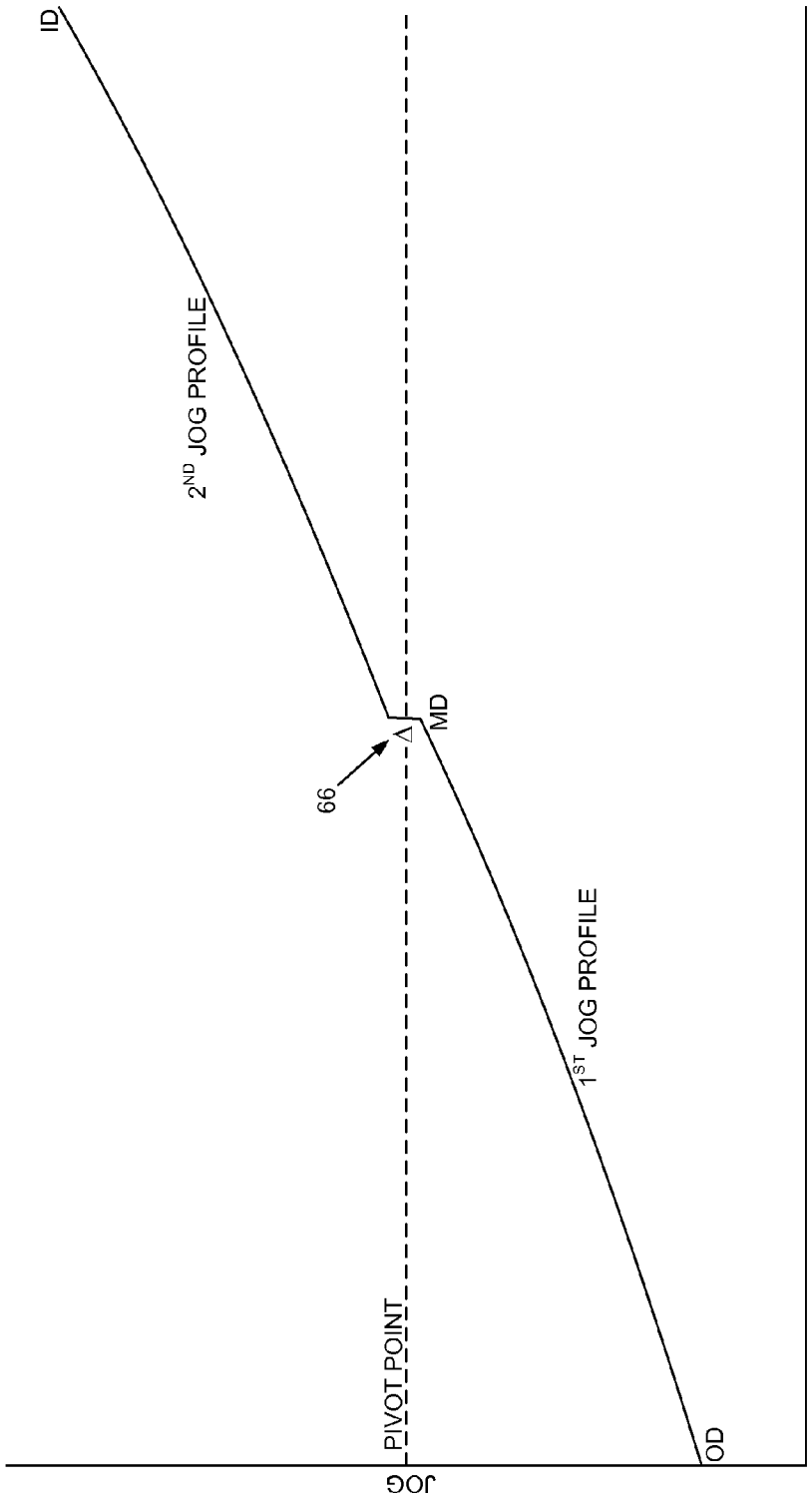
ID
2ND JOG PROFILE
66
MD
1ST JOG PROFILE
OD
DISK RADIUS
PIVOT POINT
JOG

FIG. 5

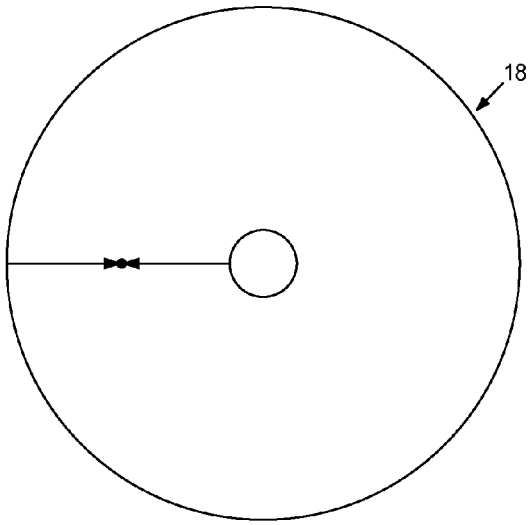

FIG. 6A

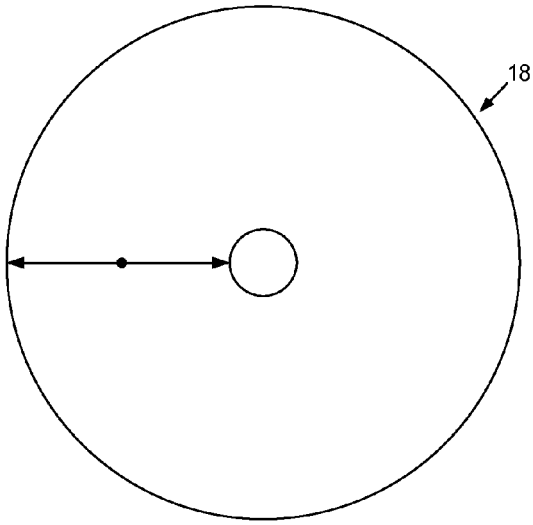

FIG. 6B

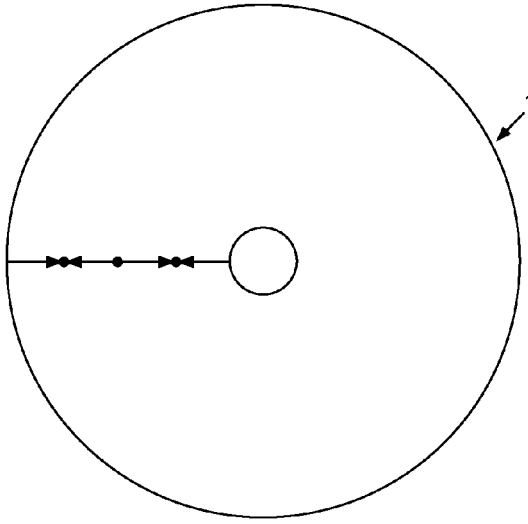

FIG. 6C

DATA STORAGE DEVICE EMPLOYING MULTIPLE JOG PROFILES FOR A BUTTERFLY WRITTEN DISK SURFACE

BACKGROUND

Data storage devices such as disk drives comprise a disk and a head connected to a distal end of an actuator arm which is rotated about a pivot by a voice coil motor (VCM) to position the head radially over the disk. The disk comprises a plurality of radially spaced, concentric tracks for recording user data sectors and servo sectors. The servo sectors comprise head positioning information (e.g., a track address) which is read by the head and processed by a servo control system to control the actuator arm as it seeks from track to track.

FIG. **1** shows a prior art disk format **2** as comprising a number of servo tracks **4** defined by servo sectors **60**-**6**N recorded around the circumference of each servo track. Each servo sector **6***i* comprises a preamble **8** for storing a periodic pattern, which allows proper gain adjustment and timing synchronization of the read signal, and a sync mark **10** for storing a special pattern used to symbol synchronize to a servo data field **12**. The servo data field **12** stores coarse head positioning information, such as a servo track address, used to position the head over a target data track during a seek operation. Each servo sector **6***i* further comprises groups of servo bursts **14** (e.g., N and Q servo bursts), which are recorded with a predetermined phase relative to one another and relative to the servo track centerlines. The phase based servo bursts **14** provide fine head position information used for centerline tracking while accessing a data track during write/read operations. A position error signal (PES) is generated by reading the servo bursts **14**, wherein the PES represents a measured position of the head relative to a centerline of a target servo track. A servo controller processes the PES to generate a control signal applied to a head actuator (e.g., a voice coil motor) in order to actuate the head radially over the disk in a direction that reduces the PES.

Data is typically written to data sectors within a data track by modulating the write current of a write element, for example, using a non-return to zero (NRZ) signal, thereby writing magnetic transitions onto the disk surface. A read element (e.g., a magnetoresistive (MR) element) is then used to transduce the magnetic transitions into a read signal that is demodulated by a read channel. The read element may be offset radially from the write element, and therefore when writing to the disk and/or when reading from the disk a "jog" value is added to the servo system to account for the writer/reader offset. Since the jog value may change across the radius of the disk due to the skew angle of the head, prior art disk drives typically calibrate a jog profile that spans the radius of each disk surface. The jog profile is then used to generate a jog value corresponding to the radial location of the head when accessing a target data track on the disk surface.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a prior art disk format comprising a plurality of servo tracks defined by servo sectors.

FIG. **2**A shows a data storage device in the form of a disk drive comprising a head actuated over a disk.

FIG. **2**B shows an embodiment wherein the head comprises a write element radially offset from a read element by a writer/reader offset that varies relative to a radial location of the head over the disk.

FIG. **2**C is a flow diagram according to an embodiment wherein a first jog profile is calibrated for a first radial band that compensates for the writer/reader offset, and a second jog profile is calibrated for a second radial band that compensates for the writer/reader offset.

FIG. **3** shows an embodiment wherein data tracks are shingle written in a butterfly pattern by writing the data tracks in an overlapping manner and in opposite radial directions over the first and second radial bands.

FIGS. **4**A and **4**B show an embodiment wherein the first jog profile is offset from the second jog profile by a delta corresponding to a percent that the data tracks overlap.

FIG. **5** shows first and second jog profiles corresponding to data tracks shingle written in a butterfly pattern toward the middle diameter of the disk according to an embodiment.

FIG. **6**A shows an embodiment wherein the data tracks are shingle written from the outer diameter to the middle diameter of the disk, and shingle written from the inner diameter to the middle diameter.

FIG. **6**B shows an embodiment wherein the data tracks are shingle written from the middle diameter to the outer diameter of the disk, and shingle written from the middle diameter to the inner diameter.

FIG. **6**C shows an embodiment wherein the data tracks are shingle written in a butterfly pattern toward multiple radial locations.

DETAILED DESCRIPTION

FIG. **2**A shows a data storage device in the form of a disk drive according to an embodiment comprising a head **16** actuated over a disk **18** comprising a plurality of data tracks **20**, wherein the head **16** (FIG. **2**B) comprises a write element **20**A radially offset from a read element **20**B by a writer/reader offset **22** that varies relative to a radial location of the head **16** over the disk **18**. The disk drive further comprises control circuitry **24** configured to execute the flow diagram of FIG. **2**C, wherein a first radial band of the data tracks is written from an outer diameter of the disk toward an inner diameter of the disk (block **26**), and a first jog profile is calibrated for the first radial band that compensates for the writer/reader offset (block **28**). A second radial band of the data tracks is written from an inner diameter of the disk toward an outer diameter of the disk (block **30**), and a second jog profile is calibrated for the second radial band that compensates for the writer/reader offset (block **32**). The first radial band of data tracks is accessed using the first jog profile (block **34**), and the second radial band of data tracks is accessed using the second jog profile (block **36**).

In the embodiment of FIG. **2**A, the disk **18** comprises a plurality of servo tracks defined by servo sectors **380**-**38**N, wherein the data tracks **20** are defined relative to the servo tracks at the same or different radial density. The control circuitry **24** processes a read signal **40** emanating from the head **16** to demodulate the servo sectors **380**-**38**N and generate a position error signal (PES) representing an error between the actual position of the head and a target position relative to a target track. The control circuitry **24** filters the PES using a suitable compensation filter to generate a control signal **42** applied to a voice coil motor (VCM) **44** which rotates an actuator arm **46** about a pivot in order to actuate the head **16** radially over the disk **18** in a direction that reduces the PES. The servo sectors **380**-**38**N may comprise any suitable head position information, such as a track address for coarse positioning and servo bursts for fine positioning. The servo bursts may comprise any suitable pattern, such as an amplitude based servo pattern or a phase based servo pattern.

In one embodiment, a jog value is calibrated to account for the writer/reader offset **22** between the write element **20**A and the read element **20**B (FIG. **2**B). For example, in embodiment during write operations the read element **20**B may be servoed over a target servo step of a target servo track that corresponds to a target data track, and then data may be written at whatever radial location the write element **20**A lands. To read the written data track, the read element **20**B is positioned over a radial location equal to the original radial location during the write operation plus the calibrated jog value. In this embodiment, the written data will align at various different fractional locations between the servo tracks as the writer/reader offset changes with the skew angle of the head (FIG. **2**B). In an alternative embodiment, a jog value may be introduced into the servo system during the write operations so that the written data is always substantially aligned at the same radial location with respect to the servo tracks (e.g., aligned with the center of the servo tracks). In either case, different jog values may be employed across the radius of the disk, such as by generating a jog value based on a jog profile that is a function of the target radial location during write and/or read operations.

In one embodiment illustrated in FIG. **3**, the data tracks may be shingle written in order to increase the radial density of the data tracks, thereby increasing the capacity of the disk drive. With shingled writing, the data tracks are written in an overlapping manner such that a previously written data track may be partially overwritten by a newly written data track. FIG. **3** also illustrates an embodiment wherein the data tracks may be written in a butterfly pattern meaning that a first radial band of the data tracks are written from an outer diameter (OD) of the disk toward an inner diameter (ID) of the disk, and a second radial band of the data tracks are written from the ID of the disk toward the OD of the disk. In one embodiment, a guard band **48** may be defined comprising at least one of the data tracks at the center of the butterfly pattern which remains unused since this data track may be overwritten in both radial directions.

FIGS. **4**A and **4**B illustrate an embodiment wherein the jog value calibrated at any given radial location of the disk may be different depending on the radial direction of shingle writing. FIG. **4**A shows the example wherein the data tracks are shingle written from the OD toward the ID. When data track **50** is written, the read element **20**B**1** is servoed over radial location **52** so that the write element **20**A**1** is aligned over the data track **50** as shown. When reading the data track **50**, the read element **20**B**2** is positioned over radial location **54** which corresponds to the original radial location **52** plus the calibrated jog value **56**. The read element **20**B**2** is positioned over radial location **54** since this location represents the center of the data track **50** after being overwritten by data track **58**. If the data tracks are written in the opposite radial direction such as shown in FIG. **4**B, the read element **20**B**1** is still positioned over radial location **52** in order to write data track **50** using the write element **20**A**1**. However, when reading data track **50** shown in FIG. **4**B, the read element **20**B**2** is positioned at radial location **60** since this location represents the center of the data track **50** after being overwritten by data track **62**. The calibrated jog value **64** that represents the offset between the original radial location **52** when the data track **50** was written and the center of the data track **50** during a read operation differs from the calibrated jog value **56** shown in FIG. **4**A by a delta **66** that corresponds to a percent that the data tracks overlap. Accordingly, in one embodiment a different jog profile may be calibrated for each radial band of data tracks that are butterfly written in a particular radial direction.

FIG. **5** shows an example embodiment wherein the disk **18** may be butterfly written over two radial bands of data tracks, including a first radial band shingle written from the OD to a middle diameter (MD) of the disk, and a second radial band shingle written from the ID to the MD of the disk. A first jog profile may be calibrated for the first radial band of data tracks, and a second jog profile may be calibrated for the second radial band of data tracks. In one embodiment, a jog value may be measured at multiple radial locations within each radial band of data tracks using any suitable technique, and the resulting data points curve fitted to a suitable function, such as a polynomial that represents the jog profile across the radial band. During normal operation, the jog value may be generated based on the jog profile using the target radial location as the input to the profile function. In the example shown in FIG. **5**, the resulting first jog profile may be offset from the resulting second jog profile by the delta **66** described above with reference to FIGS. **4**A and **4**B at the transition between the first radial band and the second radial band (i.e., at the pivot point of the butterfly pattern).

FIG. **6**A shows a disk **18** shingle written using the butterfly write pattern described above (i.e., a first radial band shingle written from the OD to MD and a second radial band shingle written from the ID to MD). However, any suitable butterfly pattern may be employed. FIG. **6**B shows an example embodiment wherein the disk **18** is shingle written in a butterfly pattern that is opposite the pattern shown in FIG. **6**A. FIG. **6**C shows an example embodiment wherein the disk **18** is shingle written over two sets of radial bands, wherein each set is shingle written from OD toward ID and from ID toward OD. Other embodiments may employ any suitable combination of the butterfly patterns shown in FIGS. **6**A-**6**C, wherein in one embodiment a different jog profile may be calibrated for each of the radial bands.

Any suitable control circuitry may be employed to implement the flow diagrams in the above embodiments, such as any suitable integrated circuit or circuits. For example, the control circuitry may be implemented within a read channel integrated circuit, or in a component separate from the read channel, such as a disk controller, or certain operations described above may be performed by a read channel and others by a disk controller. In one embodiment, the read channel and disk controller are implemented as separate integrated circuits, and in an alternative embodiment they are fabricated into a single integrated circuit or system on a chip (SOC). In addition, the control circuitry may include a suitable preamp circuit implemented as a separate integrated circuit, integrated into the read channel or disk controller circuit, or integrated into a SOC.

In one embodiment, the control circuitry comprises a microprocessor executing instructions, the instructions being operable to cause the microprocessor to perform the flow diagrams described herein. The instructions may be stored in any computer-readable medium. In one embodiment, they may be stored on a non-volatile semiconductor memory external to the microprocessor, or integrated with the microprocessor in a SOC. In another embodiment, the instructions are stored on the disk and read into a volatile semiconductor memory when the disk drive is powered on. In yet another embodiment, the control circuitry comprises suitable logic circuitry, such as state machine circuitry.

In various embodiments, a disk drive may include a magnetic disk drive, an optical disk drive, etc. In addition, while the above examples concern a disk drive, the various embodiments are not limited to a disk drive and can be applied to other data storage devices and systems, such as magnetic tape drives, solid state drives, hybrid drives, etc. In addition, some

embodiments may include electronic devices such as computing devices, data server devices, media content storage devices, etc. that comprise the storage media and/or control circuitry as described above.

The various features and processes described above may be used independently of one another, or may be combined in various ways. All possible combinations and subcombinations are intended to fall within the scope of this disclosure. In addition, certain method, event or process blocks may be omitted in some implementations. The methods and processes described herein are also not limited to any particular sequence, and the blocks or states relating thereto can be performed in other sequences that are appropriate. For example, described tasks or events may be performed in an order other than that specifically disclosed, or multiple may be combined in a single block or state. The example tasks or events may be performed in serial, in parallel, or in some other manner. Tasks or events may be added to or removed from the disclosed example embodiments. The example systems and components described herein may be configured differently than described. For example, elements may be added to, removed from, or rearranged compared to the disclosed example embodiments.

While certain example embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions disclosed herein. Thus, nothing in the foregoing description is intended to imply that any particular feature, characteristic, step, module, or block is necessary or indispensable. Indeed, the novel methods and systems described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the methods and systems described herein may be made without departing from the spirit of the embodiments disclosed herein.

What is claimed is:

1. A data storage device comprising:
- a disk comprising a plurality of data tracks;
- a head actuated over the disk, the head comprising a write element radially offset from a read element by a writer/reader offset that varies relative to a radial location of the head over the disk; and
- control circuitry configured to:
  - write to a first radial band of the data tracks from an outer diameter of the disk toward an inner diameter of the disk;
  - calibrate a first jog profile for the first radial band that compensates for the writer/reader offset;
  - write to a second radial band of the data tracks from an inner diameter of the disk toward an outer diameter of the disk;
  - calibrate a second jog profile for the second radial band that compensates for the writer/reader offset;
  - access the first radial band of data tracks using the first jog profile; and
  - access the second radial band of data tracks using the second jog profile.

2. The data storage device as recited in claim **1**, wherein:
- writing to the first radial band of the data tracks comprises shingle writing to the first radial band of the data tracks;
- writing to the second radial band of the data tracks comprises shingle writing to the second radial band of the data tracks; and
- the shingle writing comprising writing the data tracks in a partially overlapping manner.

3. The data storage device as recited in claim **2**, wherein the first jog profile is offset from the second jog profile by a delta corresponding to a percent that the data tracks overlap.

4. The data storage device as recited in claim **1**, wherein:
- the first radial band of the data tracks is substantially contiguous with the second radial band of the data tracks; and
- the first jog profile is offset from the second jog profile by a delta at the transition between the first radial band and the second radial band.

5. The data storage device as recited in claim **4**, wherein:
- writing to the first radial band of the data tracks comprises shingle writing to the first radial band of the data tracks;
- writing to the second radial band of the data tracks comprises shingle writing to the second radial band of the data tracks;
- the shingle writing comprising writing the data tracks in a partially overlapping manner; and
- the delta corresponds to a percent that the data tracks overlap.

6. The data storage device as recited in claim **1**, wherein:
- writing to the first radial band comprises writing from the outer diameter of the disk toward a middle diameter of the disk; and
- writing to the second radial band comprises writing from the inner diameter of the disk toward the middle diameter of the disk.

7. A method of operating a data storage device, the method comprising:
- a disk comprising a plurality of data tracks;
- a head actuated over the disk, the head comprising a write element radially offset from a read element by a writer/reader offset that varies relative to a radial location of the head over the disk; and
- control circuitry configured to:
  - writing to a first radial band of data tracks from an outer diameter of a disk toward an inner diameter of the disk;
  - calibrating a first jog profile for the first radial band that compensates for a writer/reader offset between a write element radially offset from a read element of a head;
  - writing to a second radial band of the data tracks from an inner diameter of the disk toward an outer diameter of the disk;
  - calibrating a second jog profile for the second radial band that compensates for the writer/reader offset;
  - accessing the first radial band of data tracks using the first jog profile; and
  - accessing the second radial band of data tracks using the second jog profile.

8. The method as recited in claim **7**, wherein:
- writing to the first radial band of the data tracks comprises shingle writing to the first radial band of the data tracks;
- writing to the second radial band of the data tracks comprises shingle writing to the second radial band of the data tracks; and
- the shingle writing comprising writing the data tracks in a partially overlapping manner.

9. The method as recited in claim **8**, wherein the first jog profile is offset from the second jog profile by a delta corresponding to a percent that the data tracks overlap.

10. The method as recited in claim **7**, wherein:
- the first radial band of the data tracks is substantially contiguous with the second radial band of the data tracks; and

the first jog profile is offset from the second jog profile by a delta at the transition between the first radial band and the second radial band.

11. The method as recited in claim **10**, wherein:

writing to the first radial band of the data tracks comprises shingle writing to the first radial band of the data tracks;

writing to the second radial band of the data tracks comprises shingle writing to the second radial band of the data tracks;

the shingle writing comprising writing the data tracks in a partially overlapping manner; and

the delta corresponds to a percent that the data tracks overlap.

12. The method as recited in claim **7**, wherein:

writing to the first radial band comprises writing from the outer diameter of the disk toward a middle diameter of the disk; and

writing to the second radial band comprises writing from the inner diameter of the disk toward the middle diameter of the disk.

* * * * *